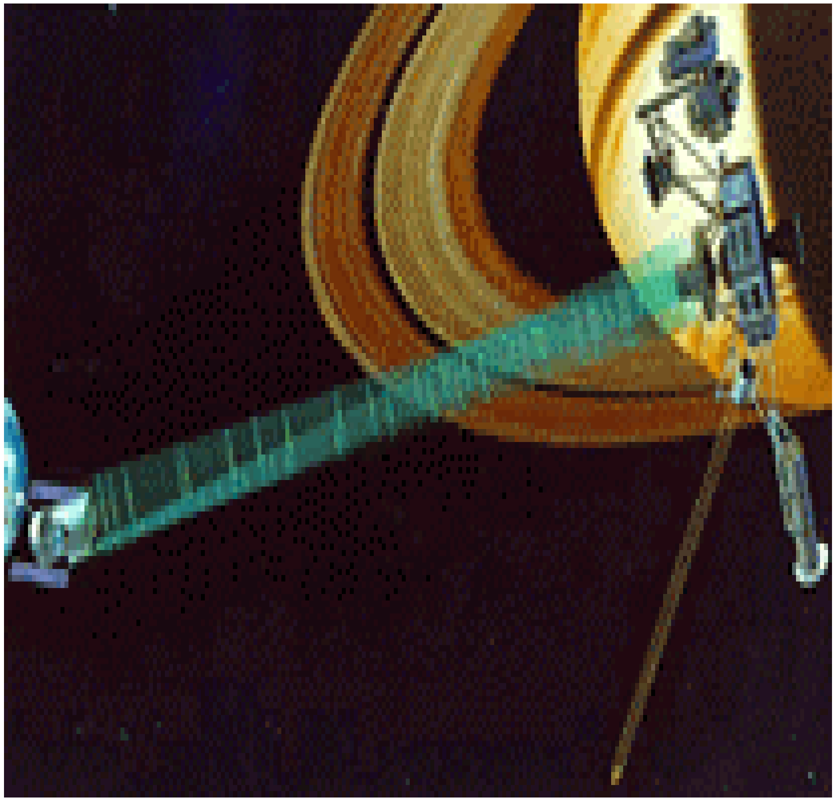


Free-Space Optical Communications at JPL/NASA

H. Hemmati

Optical Communications Group
Communications Systems and Research Sec.
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
hamid.hemmati@jpl.nasa.gov

Optical Communications - Vision and Mission

Vision:

To increase volume and timeliness of space data transfer,

to enable affordable virtual presence throughout the solar system.

Mission:

10-100 times higher data-rate,

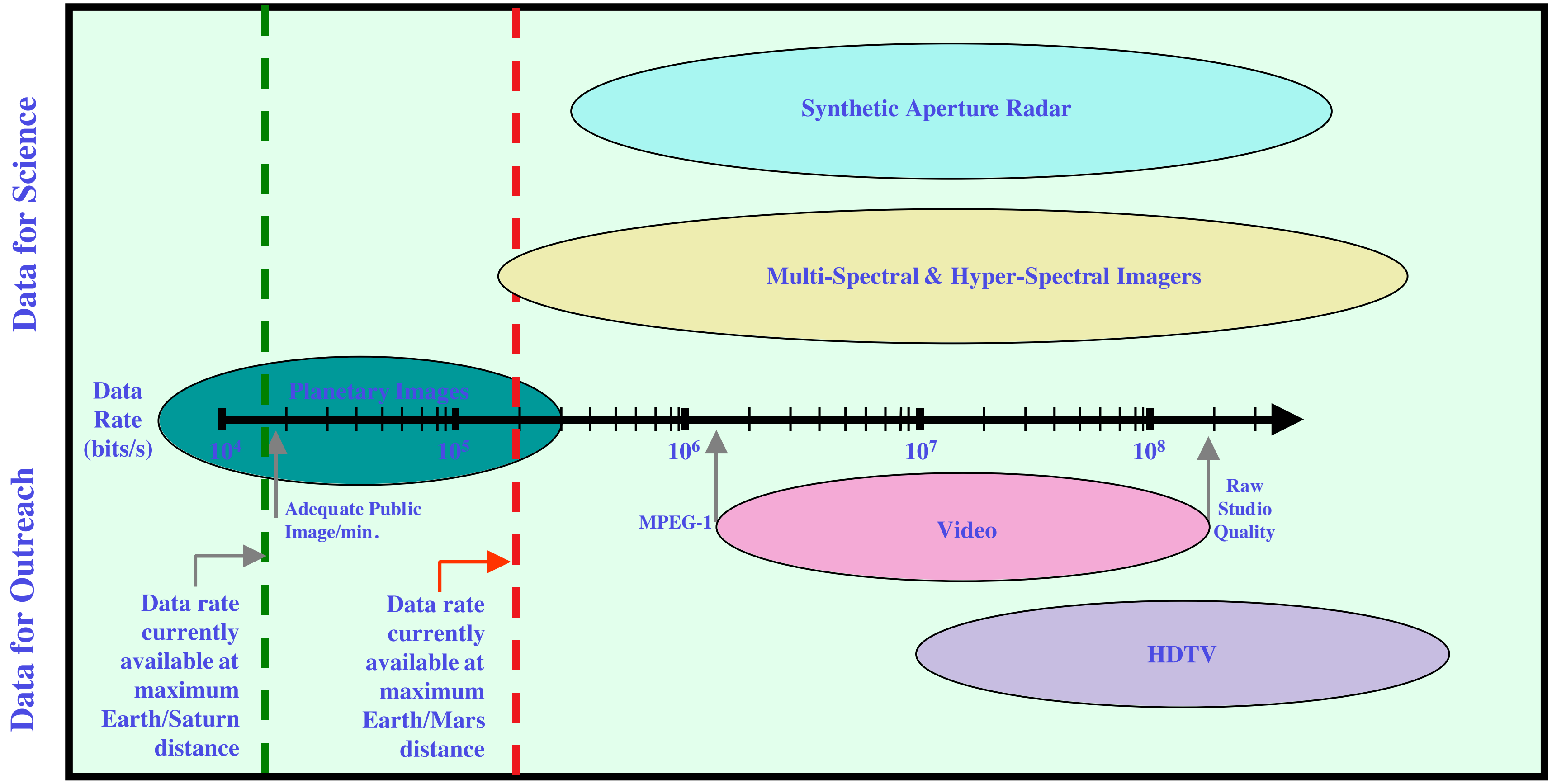
1/10 the aperture diameter,

less mass and less power consumption

…relative to current state-of-the-art.

Over the next 30 years to enhance the current communications capability (1Mbps for Mars 05) by 30 dB (3 orders of magnitude)

Future Science and Outreach Needs



Data rate requirements for science and public outreach are factors of 10 to 100 higher than can be provided by current communications technology

Mission Challenges

Current (RF) communications systems require significant spacecraft resources:

- Approximately 40-70% of the spacecraft prime power is now allocated to the communications system during peak communications period
- The percentage of the communications system dry mass increases from 2% for Venus mission to >10% for Saturn and Neptune missions
- Antenna sizes vary from 1.5 to 3 meters

Communication Challenges

- Six (6) orders of magnitude range difference from LEO to end of solar system
- Very low signal strength
- Long round trip light time from 10's of minutes to several hours
- Asymmetric data path
- Stressing thermal, radiation and shock environments
- Stressing pointing accuracy requirement for Optical Communications
- Communication signal also used for navigation
- Link availability due to atmospheric and orbit conditions
- Extremely weight, size and power limited - Need to reduce fraction of spacecraft prime power and mass allocated to the communications system without sacrificing communications performance

Performance Projections

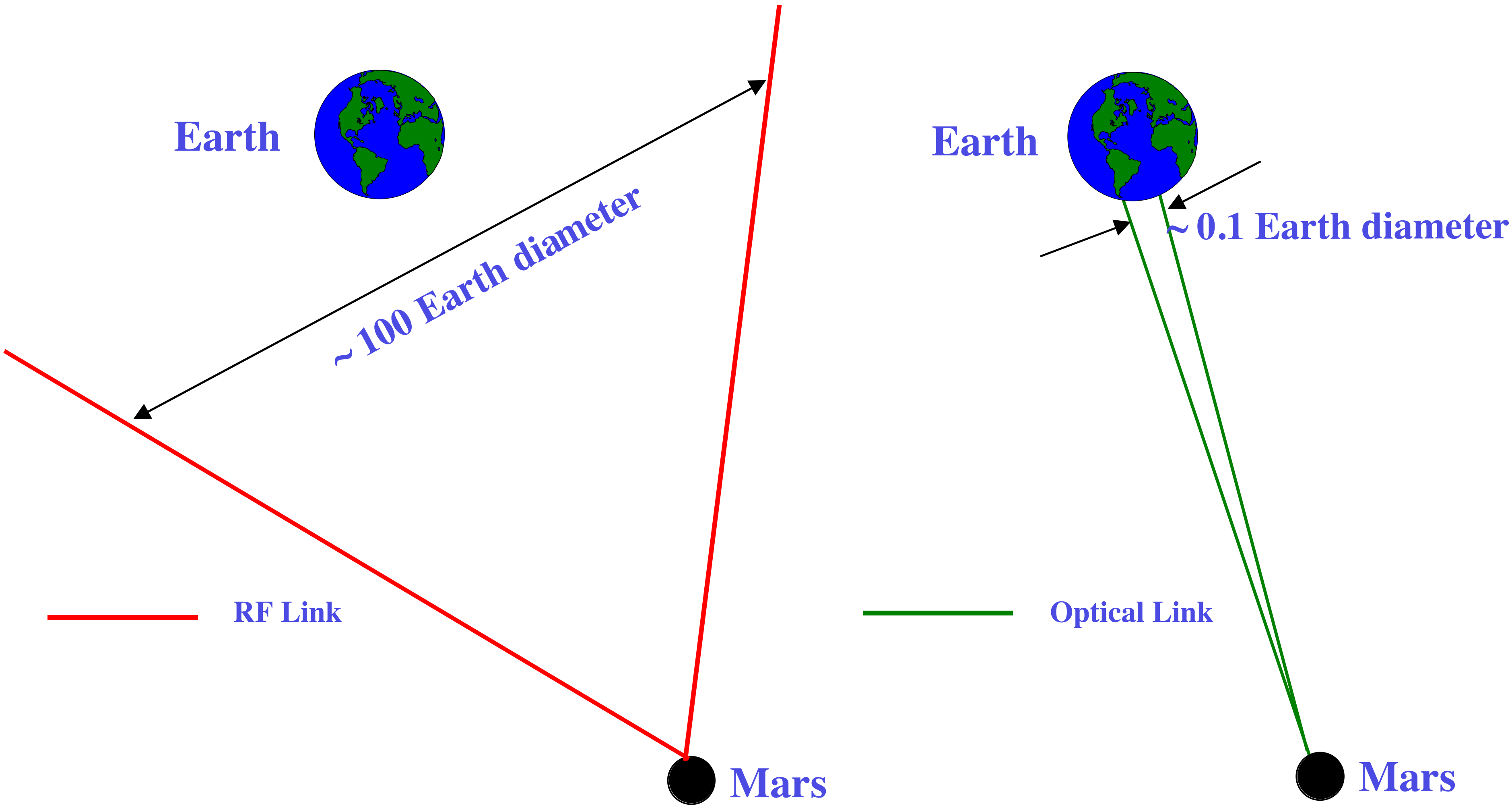
- **X-band (8 GHz)** - Current baseline capability
- **Ka-band (32 GHz)** communications (ready for infusion)
  - 11.6 dB theoretical performance gain over X-band
  - 4-6 dB enhancement available immediately; more later with improvements
- **Optical Communications**
  - ~54 dB theoretical performance gain over X-band
  - ~10 dB enhancement relative to X-band (assuming 0.3-m space aperture at maximum Mars-Earth distance and 10-m ground telescope)
  - Additional 10 dB growth potential over time as technology matures (more efficient components and larger diameter ground telescope)
- **These performance gains can be used to:**
  - Increase science data return, ***or***
  - Reduce the impact (mass/power) on spacecraft (for a given data rate), ***or***
  - Reduce required contact time with (and costs of) ground reception station support

* Assumes power consumption dominated by XMTR Power Amp

Benefit Example

A 3 dB gain can enable:
- 2x data return, ***or***
- 50% power reduction*, ***or***
- 50% reduction in GND tracking time

Beam Divergence (Frequency) Effect



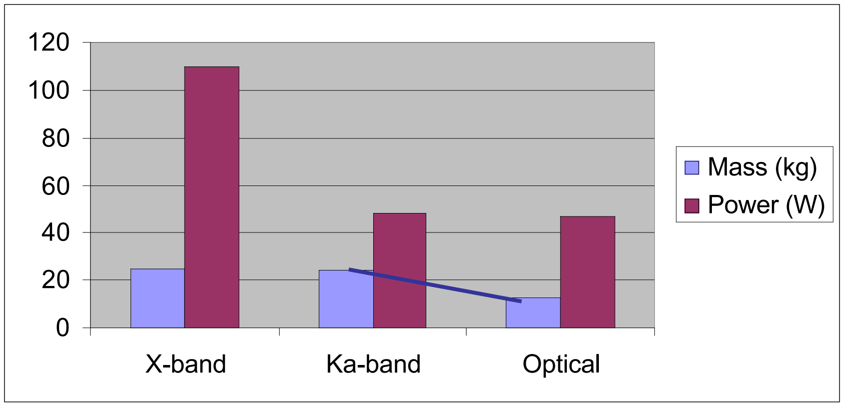
Deep Space Optical Communications
Advantages (Deep Space)

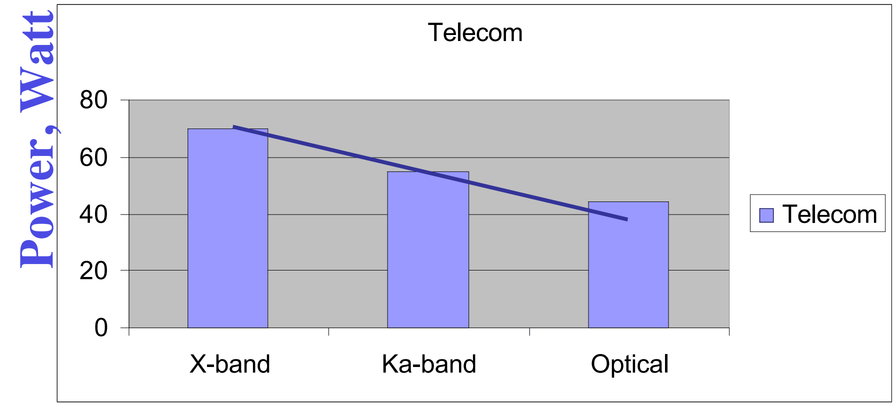
- Optical frequency provides nearly 90 dB (10^9) advantage over X-band frequency for identical antenna/telescope aperture size of both the space and ground terminals
- Aperture of a typical lasercomm flight terminal is approximately 10% of an RF system (assuming ground receiver telescope aperture is 10-m in diameter, compared with a 70-m DSN antenna)
- Current optical receivers are less efficient than RF receivers
- Current laser transmitters have less than 30% of efficiency of RF transmitters
- Additional few dB margin (nominal) is required for laser propagation through the atmosphere
    - 8-11 dB margin is available to provide over 10X higher data-rate based on the same input DC power
    - Over 10 dB margin can be recovered on top of the current advantage by improving component efficiencies through technology developments

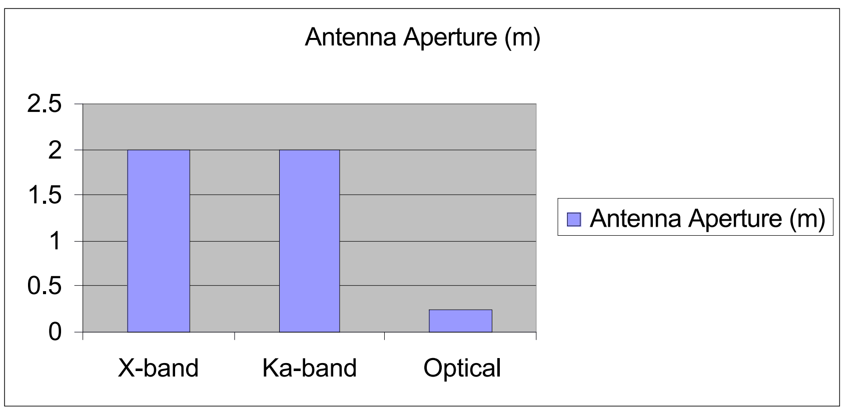
Performance Projections

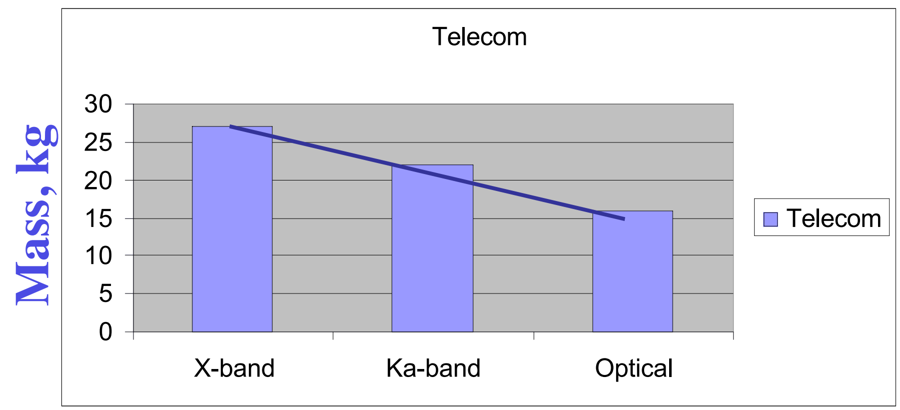
1997 Study for Mars Mission (10 Gbit volume per day)

Jupiter Deep Multi-probes Study ('09 launch)





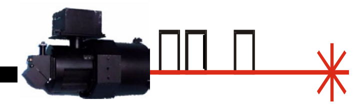




Optical communications: power and mass -- reduction of ~40% vs. X-band and aperture reduction of over 80% vs. X-band or Ka-band technology

Potential of Laser-Communication Technology

(Example - Comparison with X-band)



	Gain, Losses & Efficiency (dB)		Optical Advantage (dB)		Notes
	X	Optical	Year 2000	Year 2010	
Transmitter aperture gain (dB)	39.86	116.03	76.17	76.17	1.5 m X-band (incl. struc. losses) and 0.3 m Optical
Receiver aperture gain (dB)	74.17	149.30	75.13	75.13	70 m X-band (incl. all losses) and 10 m Optical
Space loss (dB)	-282.44	-372.90	-90.46	-90.46	Nominal range = 2.5 AU
Transmitter antenna losses (%)	-1.00	-1.25	-0.25	0.00	Surface reflectance and struts, hot body noise
Transmitter beam-path losses (%)	-1.00	-1.25	-0.25	0.00	Includes: filter, splitter, circulator, cables, ...
Pointing losses (dB)	-0.20	-2.00	-1.80	-1.40	
Transmission path losses (%),	-0.80	-1.74	-0.94	-0.94	
Receiver antenna losses (%)	-1.30	-3.67	-2.37	-1.40	X-band losses are already accounted for
Transmitter power (W)	10.97	4.77	-6.20	-3.60	Laser transmitter efficiency improvement
Data rate delivery (bps)	6.40E+04	1.50E+06			Optical provides > 20 times data-rate advantage
Required power/data rate (W.sec/bit)	-214.44	-177.74	-36.70	-34.60	Receiver detector efficiency improvement
			12.33	**18.90**	Net advantage (assuming night-time reception)
			8.80	**15.50**	Net advantage (assuming day-time reception)

Assumptions:

Link margin = 3 dB, Elevation angle = 15°, BER= 10^{-5}

DC input power for both systems = 35 W

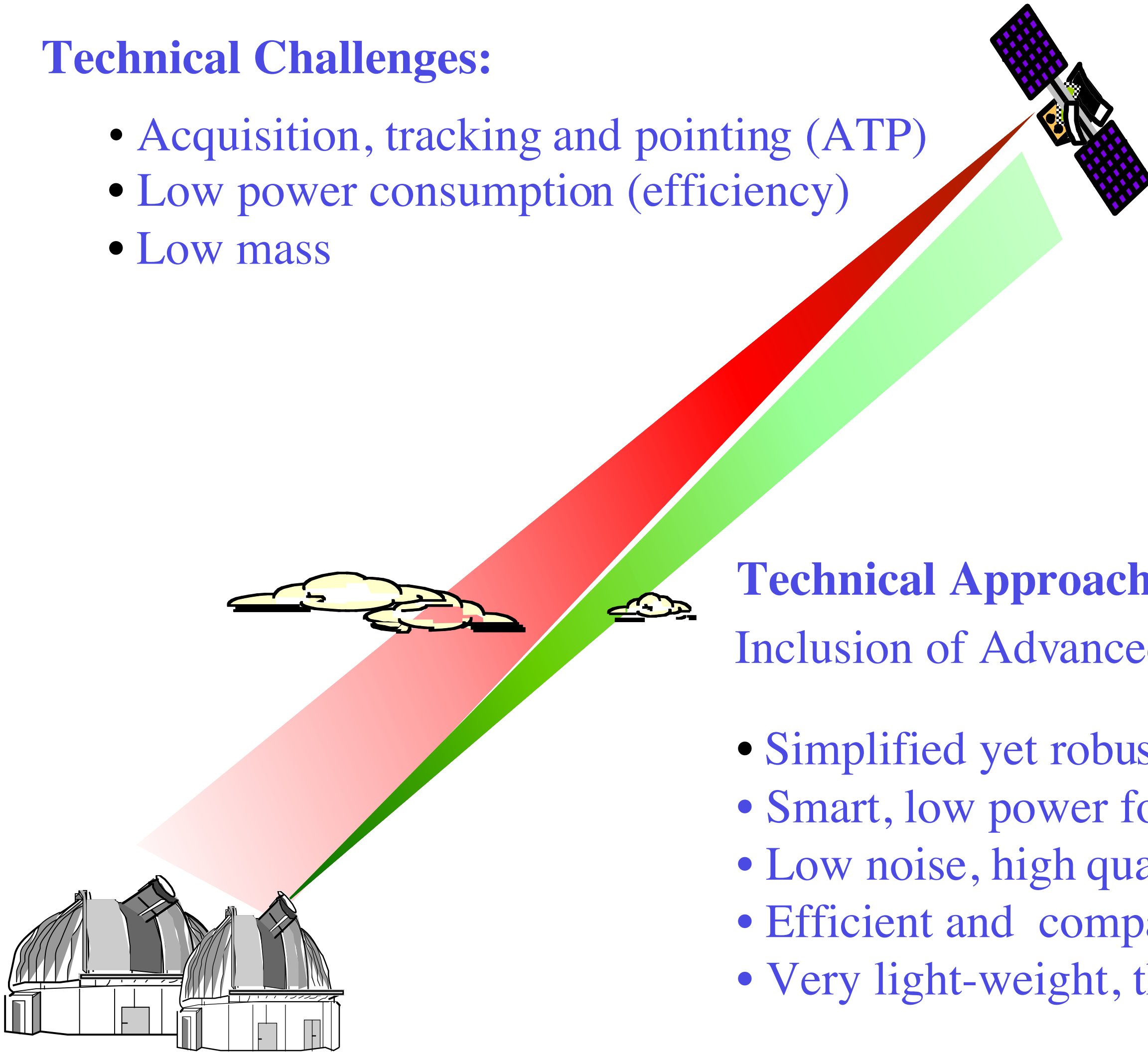
Optical: 25 W to transmitter and 10 W to acquisition and tracking subsystem

X-band: 12.5 W to transponder and 22.5 W to amplifier (55% efficiency, year 2000)

Optical Communications

Technical Challenges:

- Acquisition, tracking and pointing (ATP)
- Low power consumption (efficiency)
- Low mass

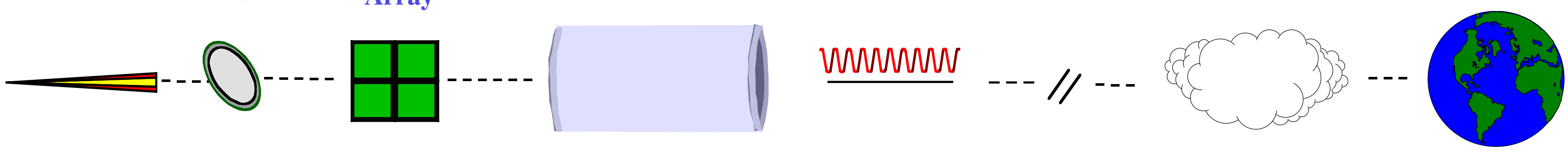


Technical Approach:

Inclusion of Advanced Technologies

- Simplified yet robust ATP architectures & algorithms
- Smart, low power focal-plane-arrays for ATP
- Low noise, high quantum efficiency data detectors
- Efficient and compact solid-state laser transmitters
- Very light-weight, thermally-stable optics & structures

Design Drivers / Technology Development



Laser
- Efficiency
- Power vs. data rate
- Extinction ratio
- Reliability

Fine-Pointing Mirror
- Bandwidth
- Reaction
- Performance
- Reliability

Focal Plane Array
- Type
- Array size
- Pixel size
- Noise
- Spectral band
- Field-of-view
- Dynamic range
- Sensitivity
- Readout rate
- Update rate
- Processing power
- Stray sun light
- Scattered transmit light
- Reliability
- SPE & SEP angles
- Acquisition time

Receiver (Optics)
- Aperture size
- Field-of- view
- Xmt-Rcv isolation
- Sensitivity
- Duplex operation
- Thermal effects
- Optics contamination

Platform
- Vibration environment (S/C jitter) - unknown
- Deadband cycle
- Earth exposure time

Space
- Radiation

Atmosphere
- Visibility
- Cloud cover
- Attenuation
- Elevation angle
- Sun angle
- Solar loading
- Turbulence
- Scattering

Earth
- Reflectance
- Albedo variations
- Crescent size
- Motion

Validation Strategy/Approach

– Develop flight terminal engineering model (2002 - 2005)

– Conduct series of flight demonstrations from 2005 through 2010

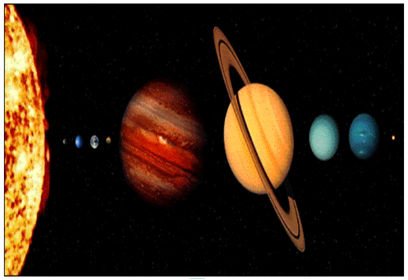
- Validate high efficiency and moderate power laser transmitters
- Validate precision tracking and pointing mechanism to planetary requirements

– Develop techniques for atmospheric effect mitigation (e.g. adaptive optics and smart focal plane detector arrays) and validate in the optical R&D station

– Develop plans and technologies for 10 meter optical ground stations infrastructure

Technology Roadmap

Mars
& Outer
Planetary



Neptune
Orbiter

Key Milestones to be achieved

- Miniaturization
- Radiation Harden

2000
- 10% Efficient Laser with < 1 Mbps modulation
- 30% Detector Quant. Effic.
- 1 urad pointing

2005
- >20% efficient laser with >10 Mbps modulation
- 8 photons/bit detection
- 0.25 urad pointing
- 10-12 kg terminal

2010
- 30% Efficient 10 W laser with > 100 Mbps modulation
- 4 photons/bit detection
- 50 nrad pointing
- <7 kg terminal

1-m R&D Optical Station

10-m Ground Receiver Infrastructure Ready

2000 2005 2010 2015

Current Optical Comm Activities

- **NASA Code R funded activities**
  - Next generation Optical Communications Demonstrator technologies
    - Acquisition, Tracking and Pointing (ATP) for sub-micro-radian pointing of laser beams to Earth
    - Efficient laser components for near-Earth and deep space
    - High bandwidth focal plane arrays and fine-pointing mirrors
    - Sensors Web for future landers using retro-modulators for communications
- **NASA Code Y funded activity (AIST NRA award)**
  - High rate communications in the rage of 1 to 10 Gbps from LEO-to-LEO or GEO-to-ground
- **NASA Code M funded activities**
  - Atmospheric Visibility Monitoring (AVM)
  - Optical Communications Telescope Laboratory (OCTL)
  - Efficient coding and modulation
  - Advanced concepts development, large aperture photon-bucket definition

Current Optical Comm Activities, Continued…

- **NASA Code S funded activities**
  - –ST-6 technology validation concept study (partnering with Ball Aerospace)
  - –Next generation Mars Lidar - providing flight-qualified lasers and detectors to a laser mapper for safe landing / hazard avoidance during future Mars missions

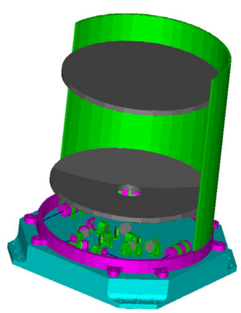
- **DOD - MDA (Missile Defense Agency)**
  - – Joint terminal development with TREX Enterprise (San Diego)
  - – 2.5 Gbps lasercomm demonstration from UAV (e.g. Predator) to ground
  - – 2.5 Gbps lasercomm demonstration from Plane (DC8) to ground

ATP Technologies - Innovation and Uniqueness

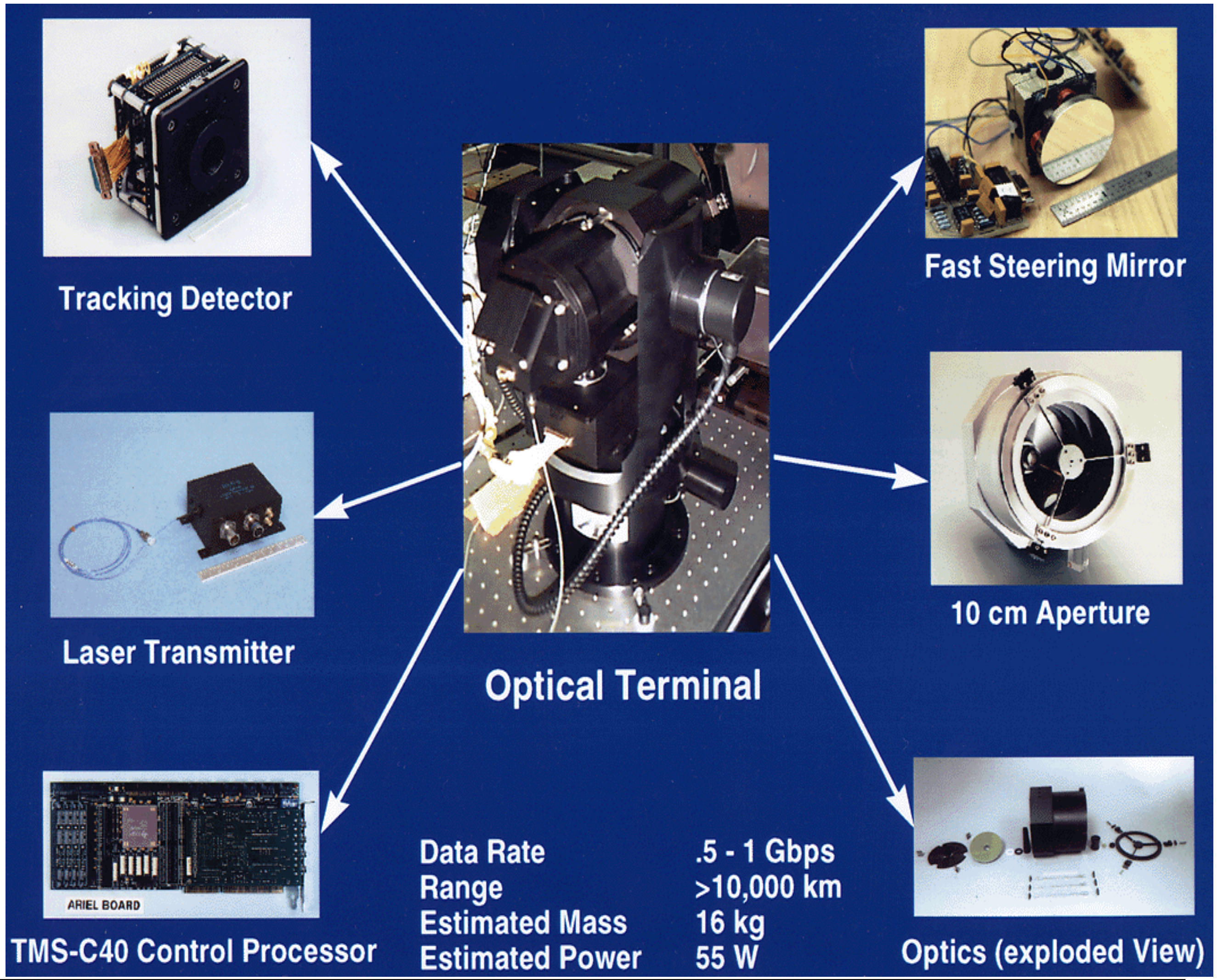
- **Technology Innovation:**
  - Unified and simple ATP architecture for entire solar system
  - Innovative integration and development of state-of-the-art components, subsystems and algorithms to address unique deep space needs
    - Which improve random and system noise and dynamic range
    - To achieve laser beam pointing accuracy to the sub-microradian level
    - While addressing > 35 AU Range, Minimal impact on S/C, Low Size, Weight and Power

- **Uniqueness of this technology:**
  - Unique to deep space optical links
    - absolute and accurate sub-microradian pointing control from *anywhere within the solar system and beyond*
    - enables greater than an order magnitude improvement in data-rate delivery from space to Earth

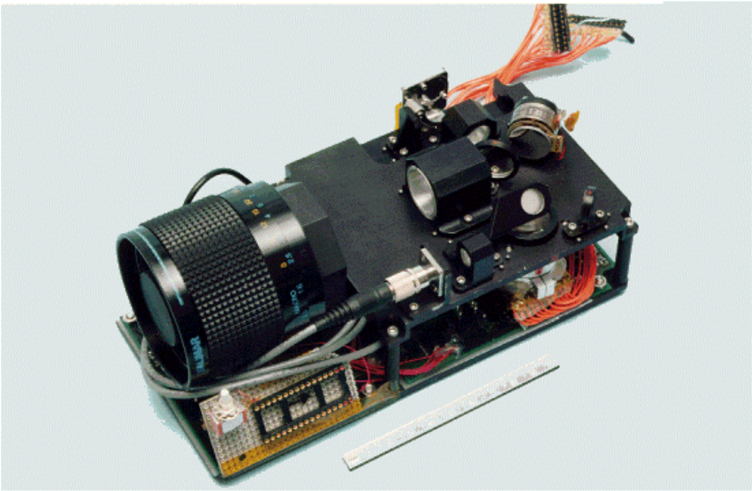
Optical Communication Demonstrator (OCD, laboratory model)



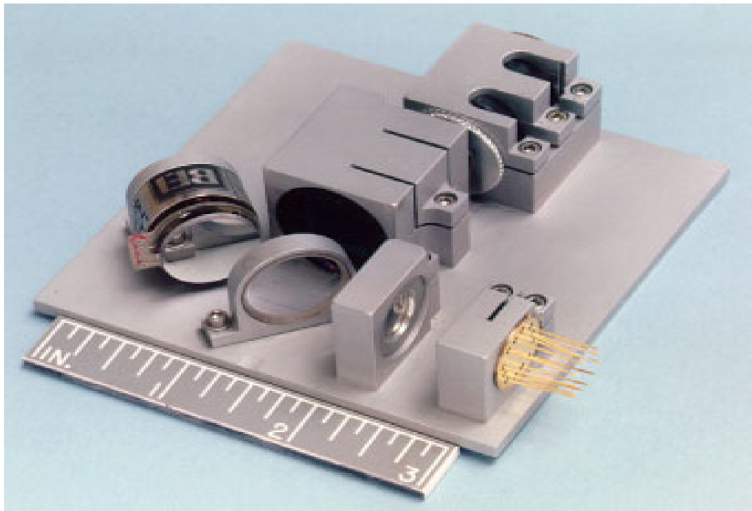
Next Generation



Low-Capability Lasercomm Terminals

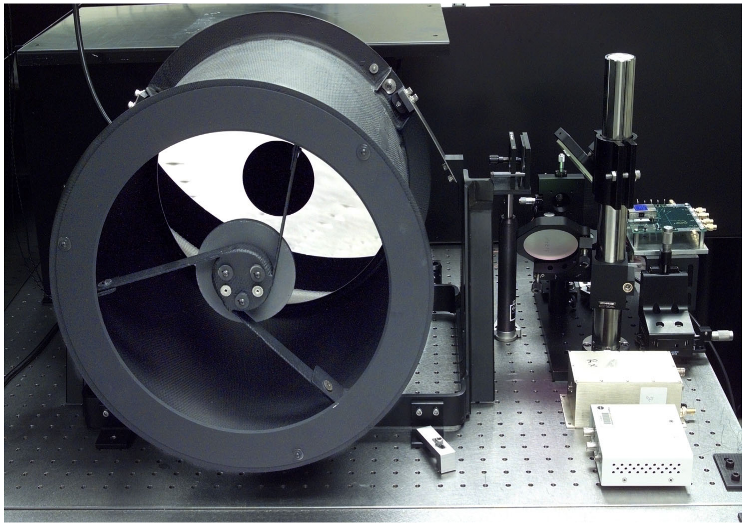


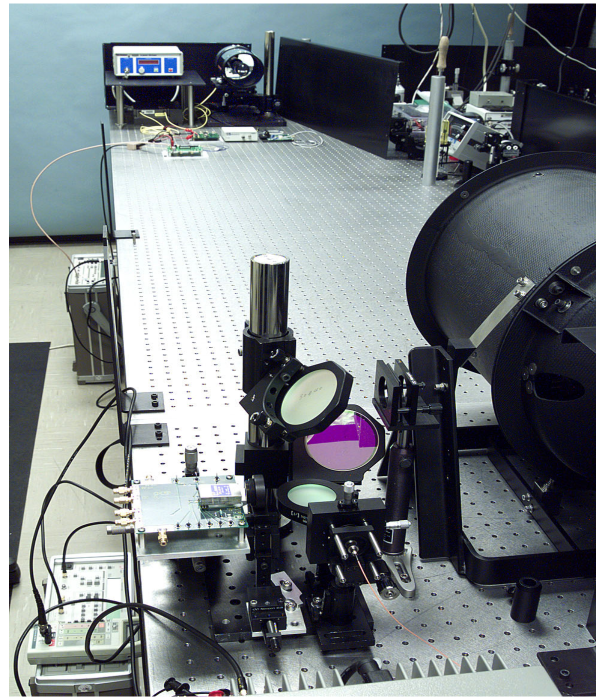
ACLAIM
(A Combined Lasercomm and Imager for Micro-spacecraft)



SCOPE
(Small Communications Optical Package Experiment)

2.5 Gbps Optical Comm Links Depicting Data transmission from LEO-to-GEO



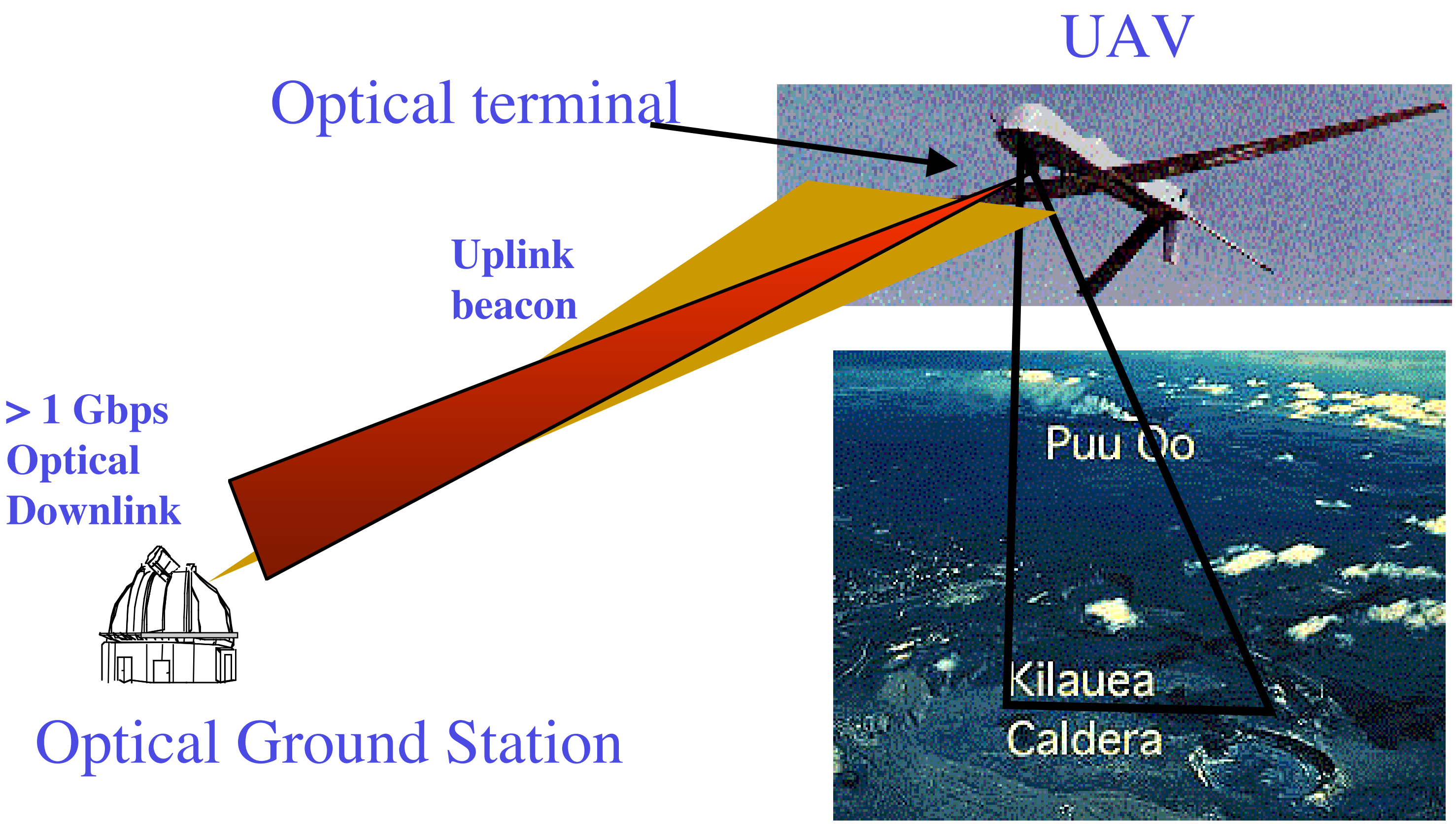


Objective:

Develop communications (in the range of 1 to 10 Gbps) and acquisition, tracking and pointing technologies for lasercomm to transmit science data from LEO-to-GEO or GEO-to-ground.

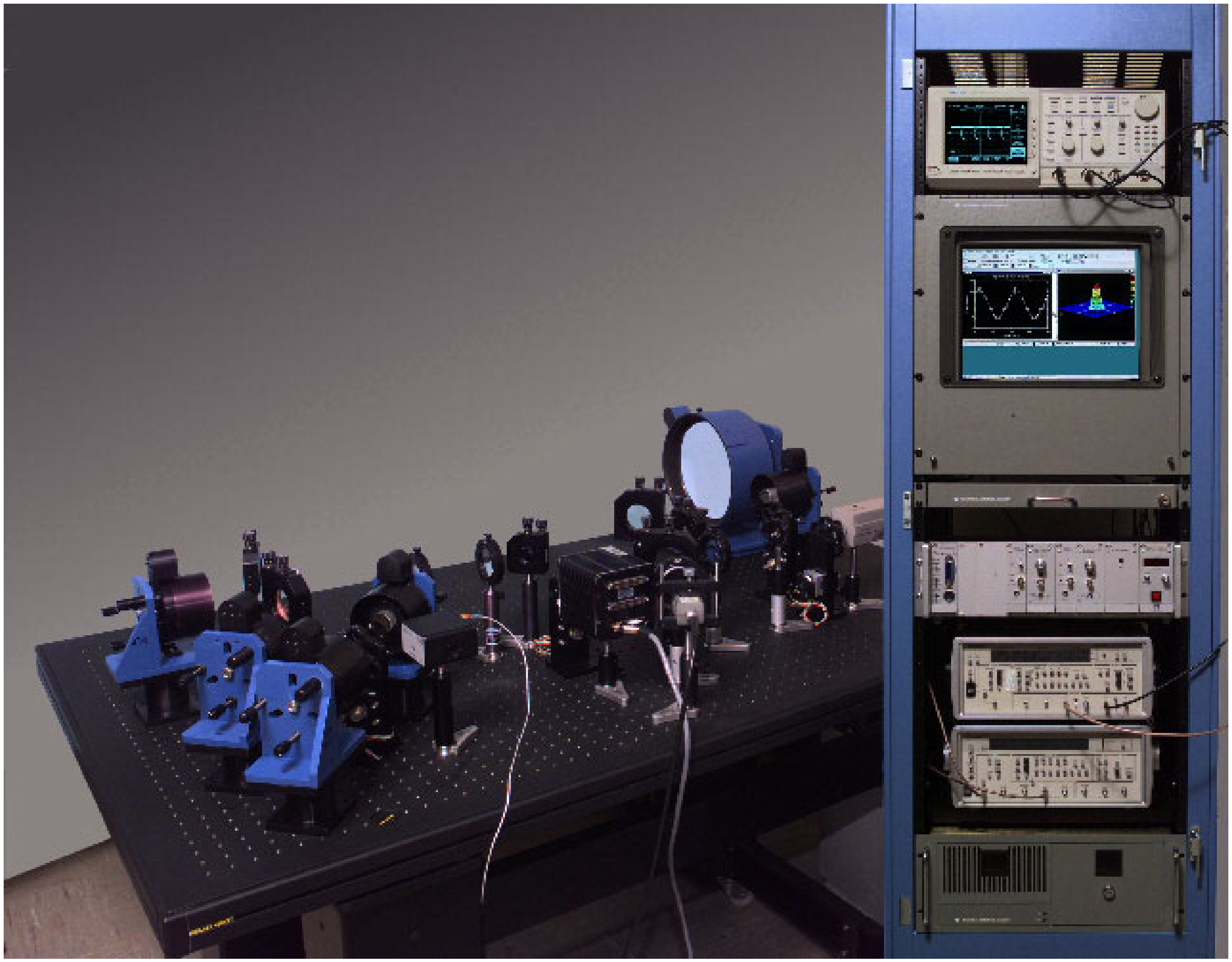
UAV Downlink Demonstration - Overview

Downlink of science data at the rate of 1 to 2.5 Gbps
from a plane (DC8) and a UAV to ground



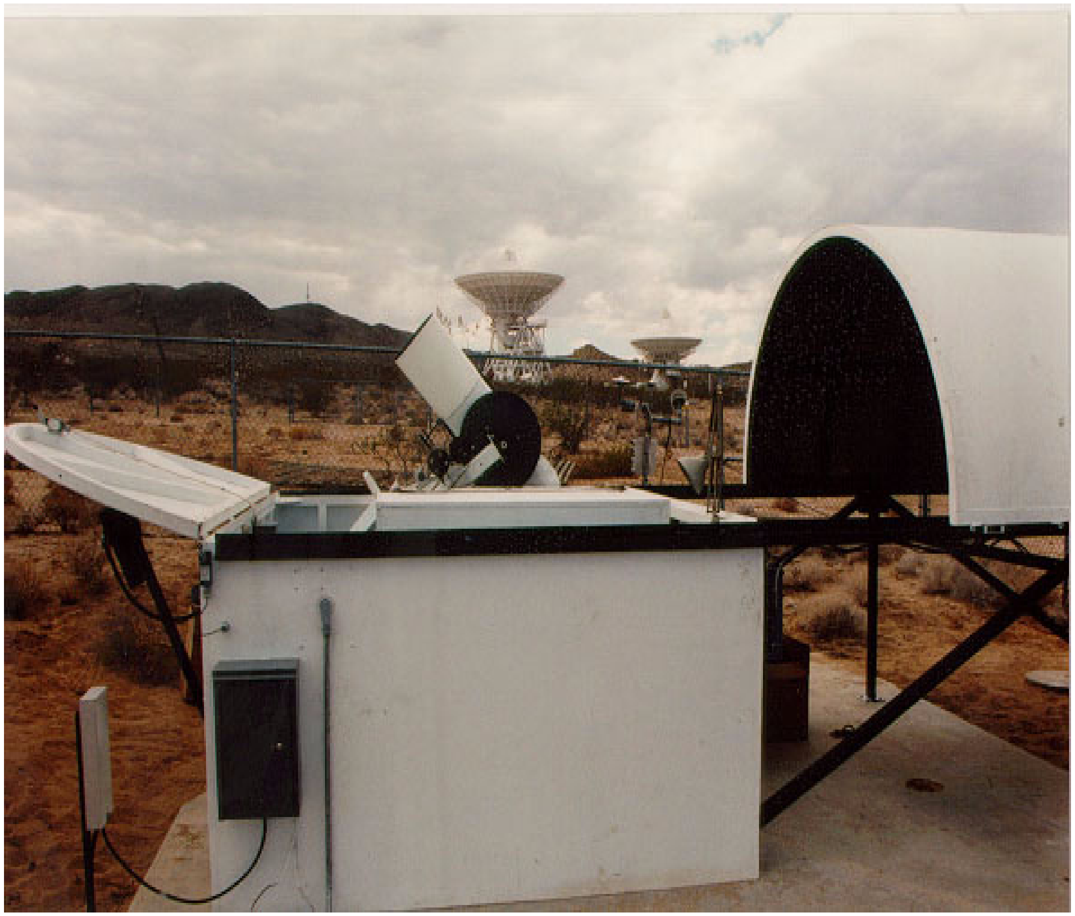
LTES

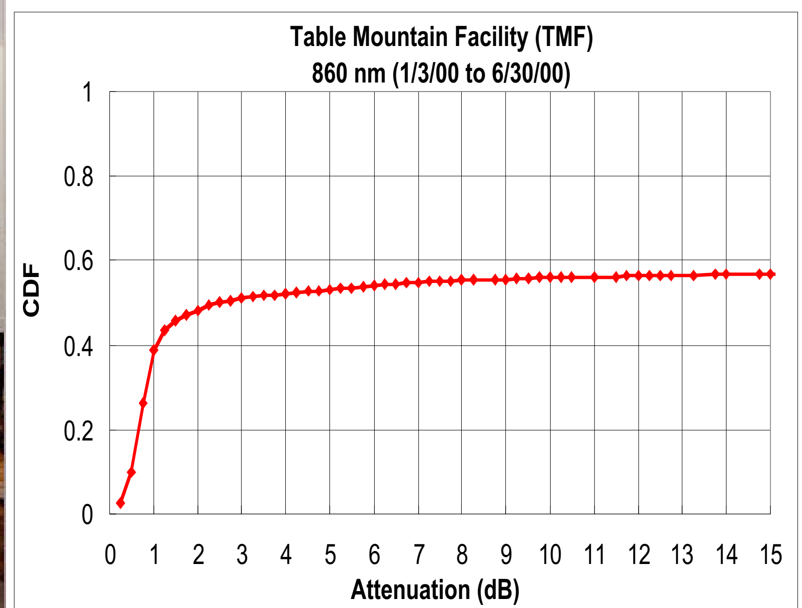
(Lasercomm Test & Evaluation Station)



AVM
(Atmospheric Visibility Monitoring)

Set of three 25-cm diameter autonomous telescopes to measure atmospheric visibility

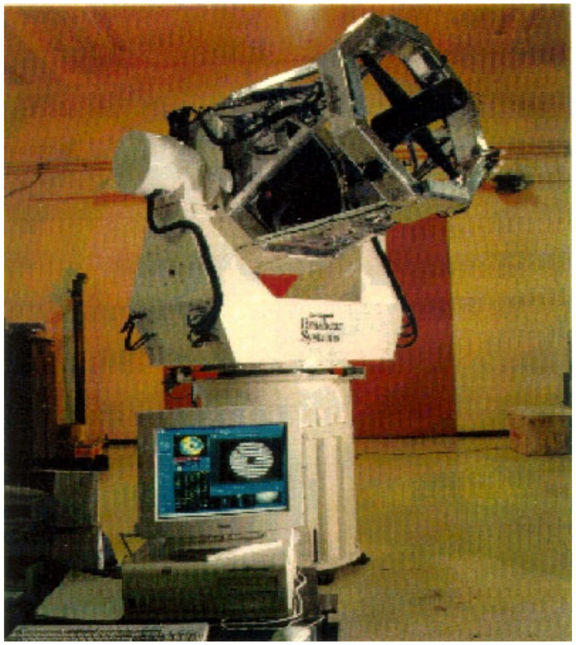




OCTL

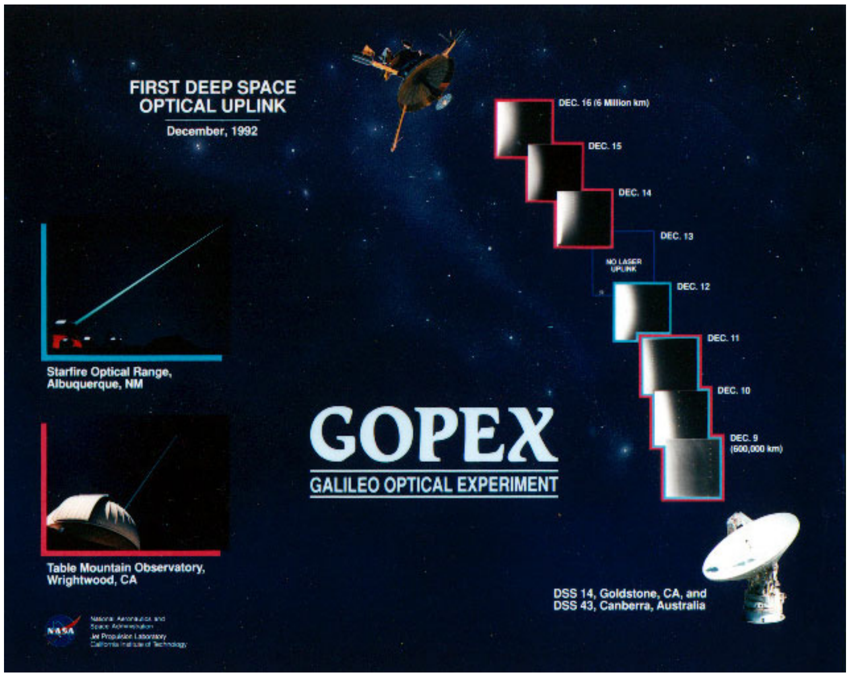
(Optical Communications Telescope Laboratory)

- A 1-m telescope facility to track LEO Spacecraft, dedicated to lasercomm
- Awarded 1-m telescope contract to Contraves Brashear January of 2000
- Telescope to be delivered Summer of 2002



GOPEX (Galileo Optical Experiment) & GOLD (Ground-to-Orbit Lasercom Demo)

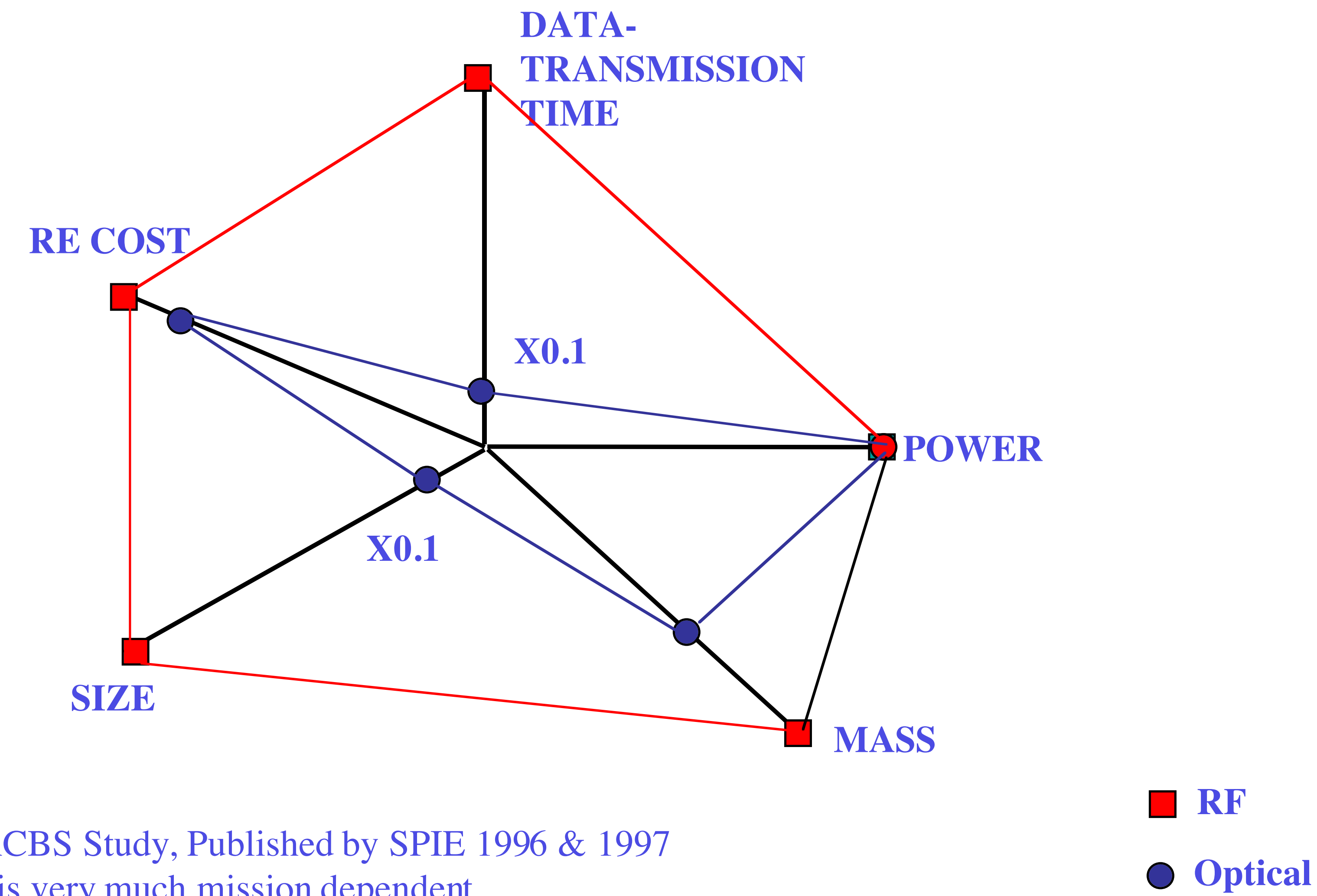
Successful experiments with spacecrafts:



Uplink to Galileo spacecraft at 6E9 m range

Uplink and downlink with ETS S/C in GEO-type orbit

Promise of Optical Comm Technology over RF Systems



Reference: ACBS Study, Published by SPIE 1996 & 1997
Performance is very much mission dependent

Technology Needs

- Low-mass and low-thermal expansion telescopes
- Effective mitigation of sunlight and scattered light in the lasercomm terminal
- A complete set of robust ATP algorithms for the 0.01 to > 35 AU range and 50 to 250 nrad pointing jitter
- An end-to-end software model for ATP
- High efficiency, low-noise receivers capable of detecting better than 4 to 8 photons/bit detectivity
- High update rate (> 5 KHz) detector arrays
- High bandwidth (> 3 kHz) 2-axis fine-pointing mirrors
- High efficiency (> 20%), medium power, solid state lasers with 10's of Mbps modulation capability
- Development of efficient modulation and coding techniques
- Development of high transmittance (>90%), narrow (~ 0.1 nm) bandpass filters at key laser wavelengths.
- Daytime adaptive optics for atmospheric effect mitigation
- Large aperture (≥10 meter), low-cost (<$20 M) non image quality telescope with ~ 30 μrad field-of-view
- Multi-function architectures combining science imaging, laser altimeter reception, and optical communications in a single instrument

Summary

- Future Solar System missions need increased communications performance to realize NASA's solar system exploration goals
  - Reduce impacts on host spacecraft (mass/power), or reduce Earth station reception time (costs)
  - Return more science data for a given mission investment

- Optical communications is less mature than RF (X-band and Ka-band), but offers significantly more growth potential
  - Could provide one or more orders of magnitude increase in data returns for most outer planet missions
  - Should be developed for flight demonstrations during this decade, and begin operational infusion in the 2010-2012 timeframe

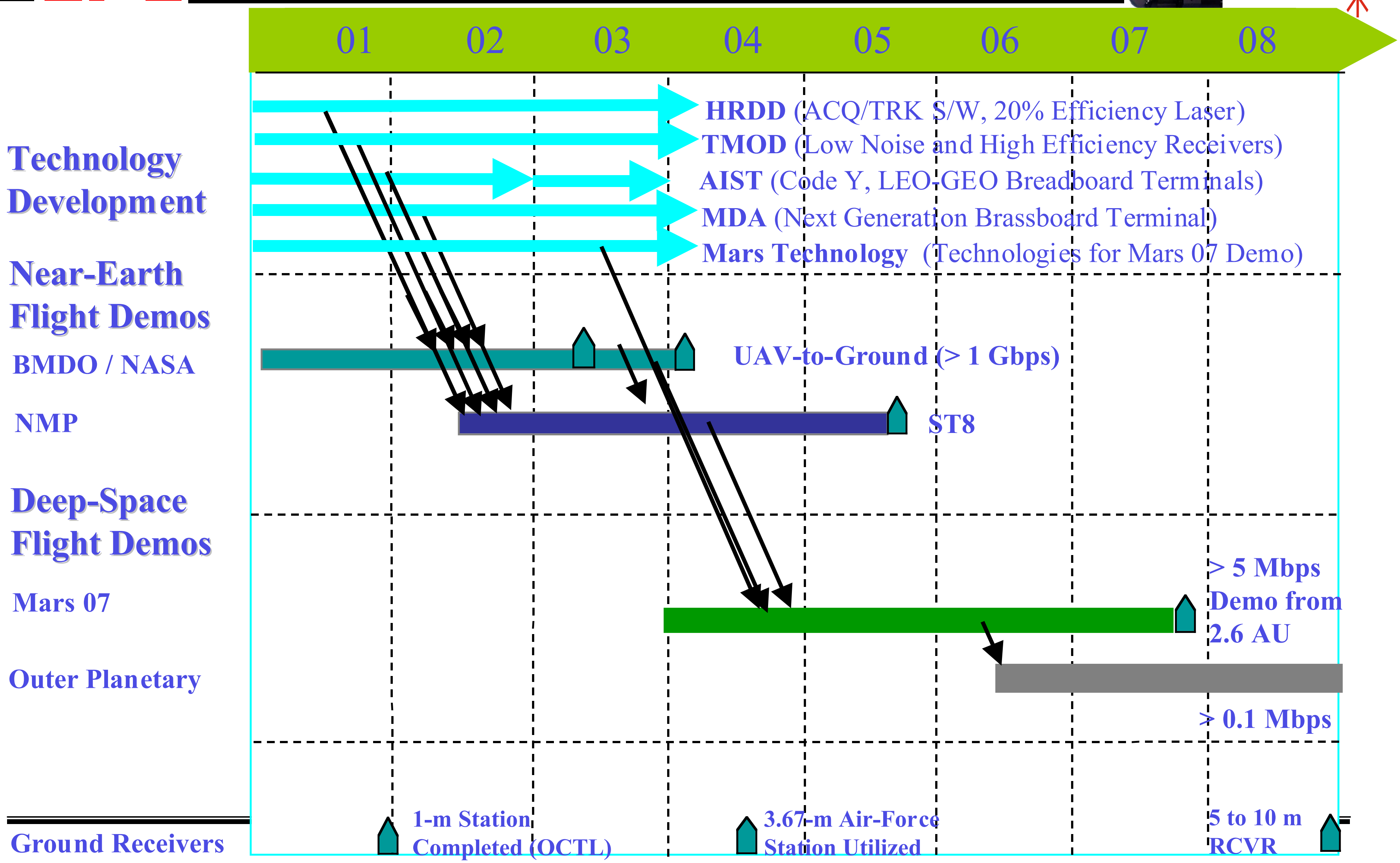
Conclusion

- Component efficiency improvements are now underway
- Solutions to remaining technology challenges are being identified / developed
- Flight demonstrations are being worked on
- Development of a network of large aperture ground receivers are planned

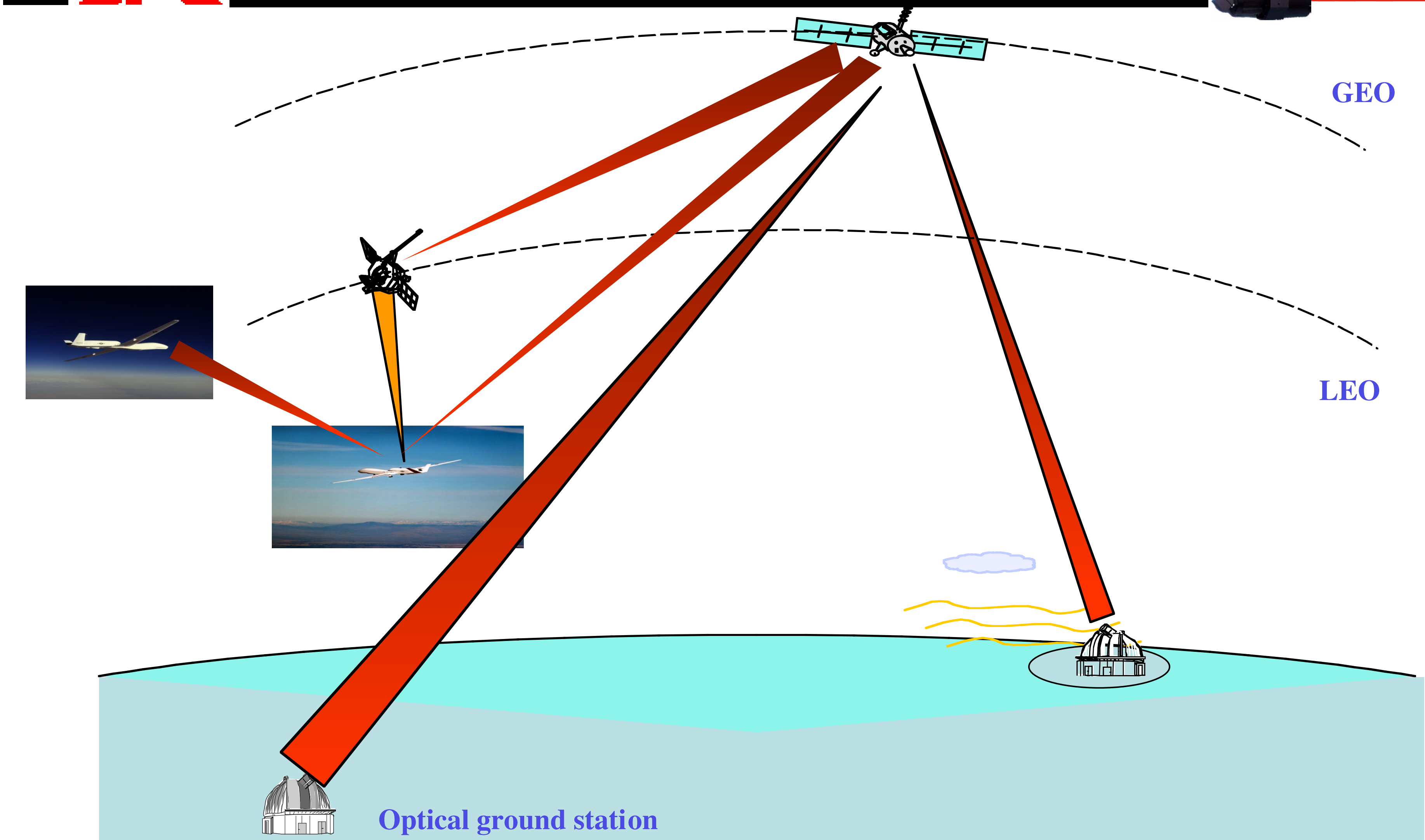
lead to establishment of a credible technology making reliable operational deep-space laser-communication a viable option

Additional Information

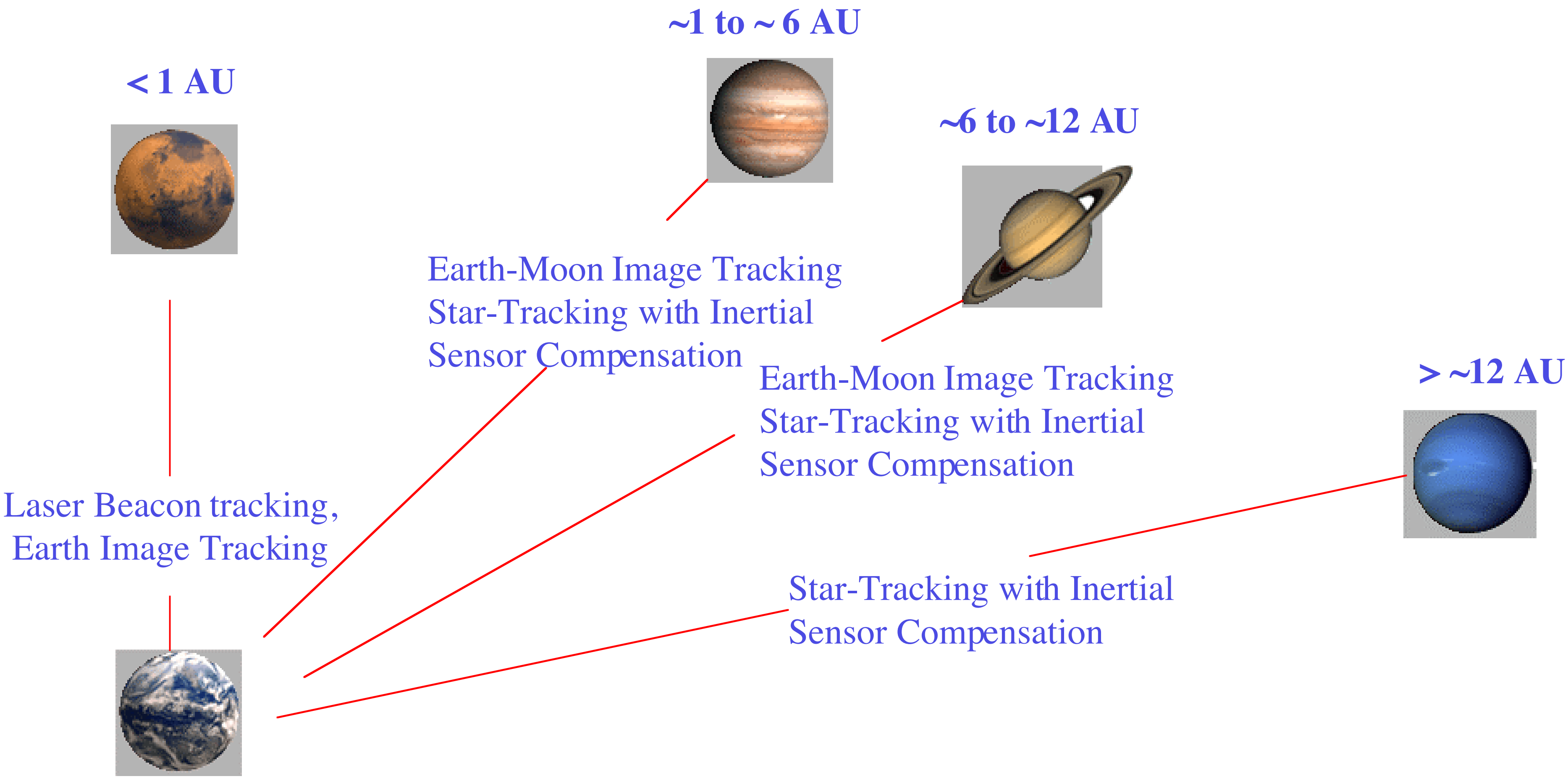
Optical-Communications Roadmap



Near-Earth Applications

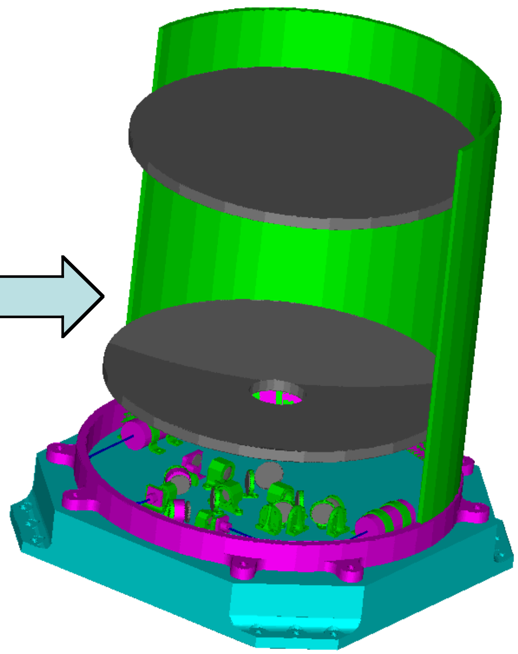


ATP Technologies for Deep Space Missions



Multi-Functionality

Laser-Communications

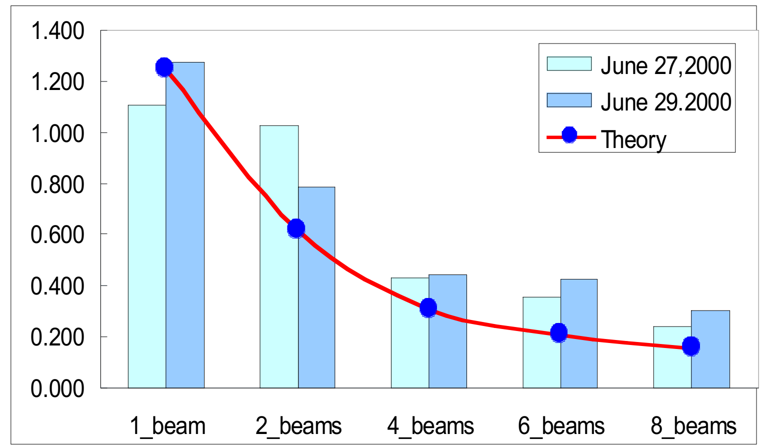


High-Resolution Science Imaging

Hazard-Detection & Avoidance (for landing) &Laser-Altimetry

Systems Level Demonstrations

- **Characterized beacon performance using 46.8 Km range mountain-to-mountain optical link from JPL's Table Mountain Facility in Wrightwood, CA to Strawberry Peak (SP)**



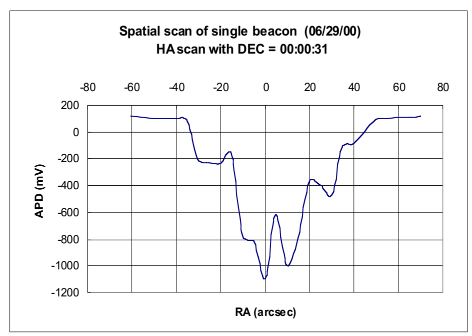
Normalized variances observed with 1, 2, 4, 6 and 8 beams

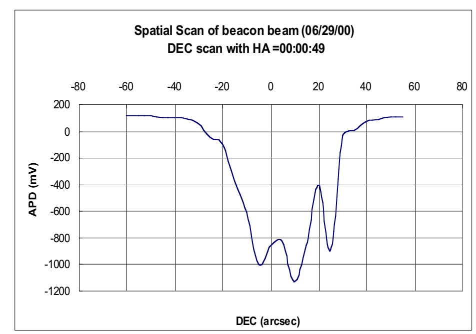
- **Demonstrated reduction in atmospheric turbulence induced irradiance fluctuations (fades) over 4 air-mass path**
  - observed 75-82% reduction in normalized variance
  - theory predicted 87% reduction
  - no fades observed with 6- and 8-beams

- **Measured individual beam divergence of 300-380 mrad compared to design goal of 100 mrad**
  - discrepancy in divergence is due to the multi-mode beam
  - transmitted power from TMF is 200 mW
  - expected average power at SP 1.02 nW for all 8-beams
  - received power at SP 1.57 - 2.32 nW

- **Estimated r0 from measured spot size on OCD**
  - measured 80-96 mm
  - implies 4-5 cm r0 for the 8-beam beacon

- **Submitted NTR on the multi-beam beacon assembly design**

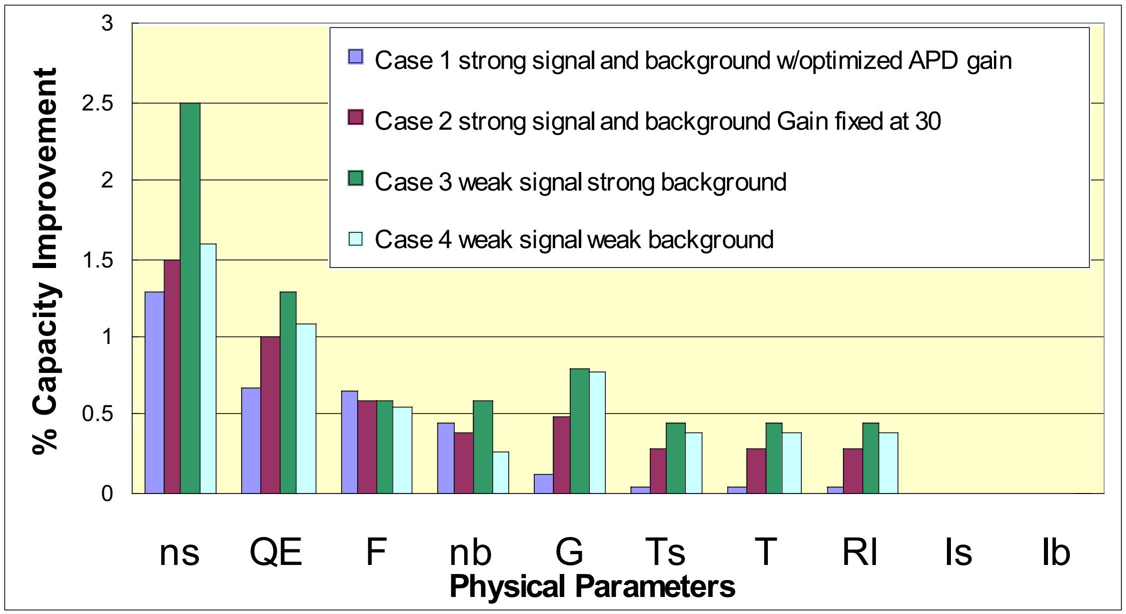




Showing typical spatial scans of single beacon beam performed by slewing TMF telescope while monitoring beacon at SP.

Optical Channel Capacity

- **Determined capacity increase for a 1% improvement in each of the ten listed physical parameters**
  - signal intensity is much more important than background noise
  - quantum efficiency is the most important detector parameter

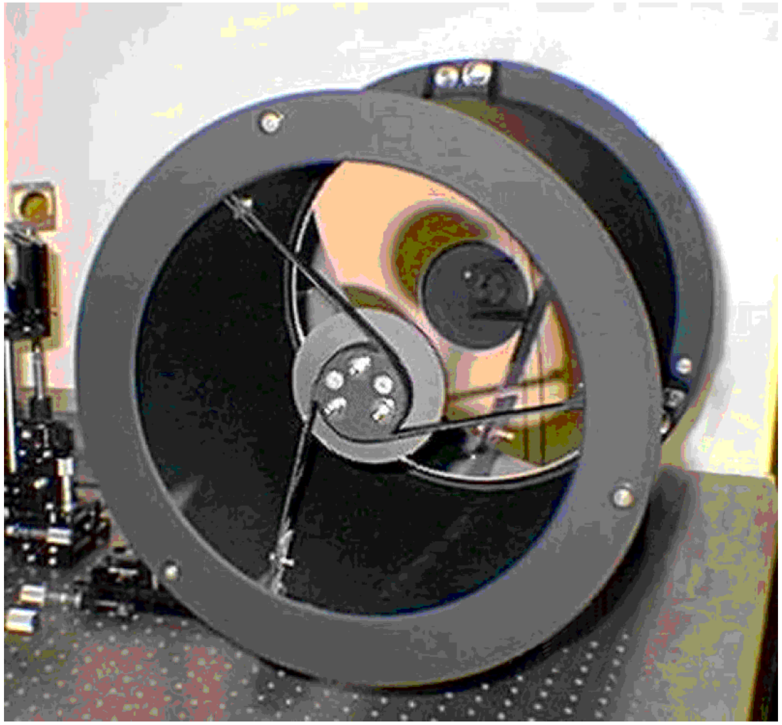


$\bar{n}s$ = mean signal photons;
η = QE;
F= excess noise factor
$\bar{n}b$ = mean background photons
G = APD gain;
Ts = slot width; T = noise temperature;
R_L = load resistor
Is/Ib = surface/bulk leakage current

- **Established the following implications :**
  - channel models considered have the same brick wall capacity limits as RF channel
  - a 3-dB gap between Soft and Hard decision PPM channels
  - gap between capacity and SOA includes 3dB due to coding and an additional 3 dB due to modulation

Lightweight Low Thermal Expansion Telescopes

- All SiC telescope
- 30-cm primary mirror
- Weight: ~ 6 kg



Developed by SSG Inc. under SBIR Phase II

Now developing a 3.5 Kg version